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TRANSPORT RATES OF Na^+, Cl^-, NO_3^- AND SO_4^{2-} BY DRIFTING SNOW AT MIZUHO STATION, ANTARCTICA

Kazuo OSADA and Keiji HIGUCHI

Water Research Institute, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-01

Abstract: Transport rates of Na^+, Cl^-, NO_3^- and SO_4^{2-} by drifting snow are estimated to evaluate the contribution to material transport process at Mizuho Station, Antarctica. Daily transport rates of Na^+ and Cl^- by drifting snow in winter are about 3 times as large as their transport rates in summer, whereas daily transport rates of NO_3^- and SO_4^{2-} in winter are two thirds of those in summer. Transport rates of chemical constituents by ice flow are also estimated to compare with the results by drifting snow. Transport rates of chemical constituents by drifting snow comprise between 9% and 18% of the amount transported by ice flow. This result indicates that not only ice flow but also drifting snow has an important role for transport of chemical constituents toward the coastal region.

Differences in NO_3^- and SO_4^{2-} concentrations (in $\mu g \cdot l^{-1}$) between ice core (56 and 51) and snow drift in summer (315 and 199, respectively) suggest that deposition of snow layer in summer probably does not occur at altitudes from 2000 m to 3000 m in the katabatic wind region. Annual transport of sulfate by drifting snow across the 2000 m contour is estimated to compare with the sulfate amount transported through the whole Antarctic atmosphere estimated by R. J. DELMAS (Nature, **299**, 677, 1982). Amount of sulfate transport (1.4×10^6 $kg \cdot yr^{-1}$) by drifting snow toward the coastal region below altitude 2000 m is three orders smaller than that through the whole Antarctic atmosphere.

1. Introduction

Drifting snow is observed through about 80% of the year at Mizuho Station (70°42′S, 44°20′E, 2230 m a. s. l.) which is located in the katabatic wind region. Mean annual wind speed is about 11 $m \cdot s^{-1}$ at Mizuho Station. In the katabatic wind region, wind redistributes an enormous mass of snow. TAKAHASHI (1988) estimated redistribution of snow drift along the flow line of Shirase Glacier, and he obtained the following results: snow drift (about 150 $mm \cdot yr^{-1}$; water equivalent converted from snow divergence) is redistributed from the middle part of the ice sheet, around the altitude of Mizuho Station, to the coastal region by the steady katabatic wind.

On the other hand, OSADA *et al.* (1989) reported on the chemical composition of snow drift collected on Mizuho Plateau in 1986. They suggested that snow drift as carrier of chemical constituents contributes to material transport over the Antarctic ice sheet. Estimation of transport rates of chemical constituents by drifting snow is important to evaluate the material cycle over the present Antarctic ice sheet, and also to interpret the past material cycle obtained by ice core analysis.

The main purposes of the present paper are to obtain transport rates of chemical

constituents by drifting snow, to compare the obtained results with transport rates of chemical constituents by ice flow at Mizuho Station. Another purpose is to compare the sulfate transport amount by drifting snow perpendicular to the 2000 m contour line with transport of sulfate through the whole Antarctic atmosphere (DELMAS, 1982), because sulfate in Antarctic snow and ice comes from background aerosol which mainly consists of H_2SO_4 (*e. g.*, MAENHAUT *et al.*, 1979; CUNNINGHAM and ZOLLER, 1981; DELMAS *et al.*, 1982a).

2. Transport Rates of Chemical Constituents by Drifting Snow

2.1. Chemical composition in snow drift at Mizuho Station

Figure 1 shows concentrations of Na^+, Cl^-, NO_3^- and SO_4^{2-} in snow drift collected on Mizuho Plateau in 1986 (OSADA *et al.*, 1989). In the present paper, "snow

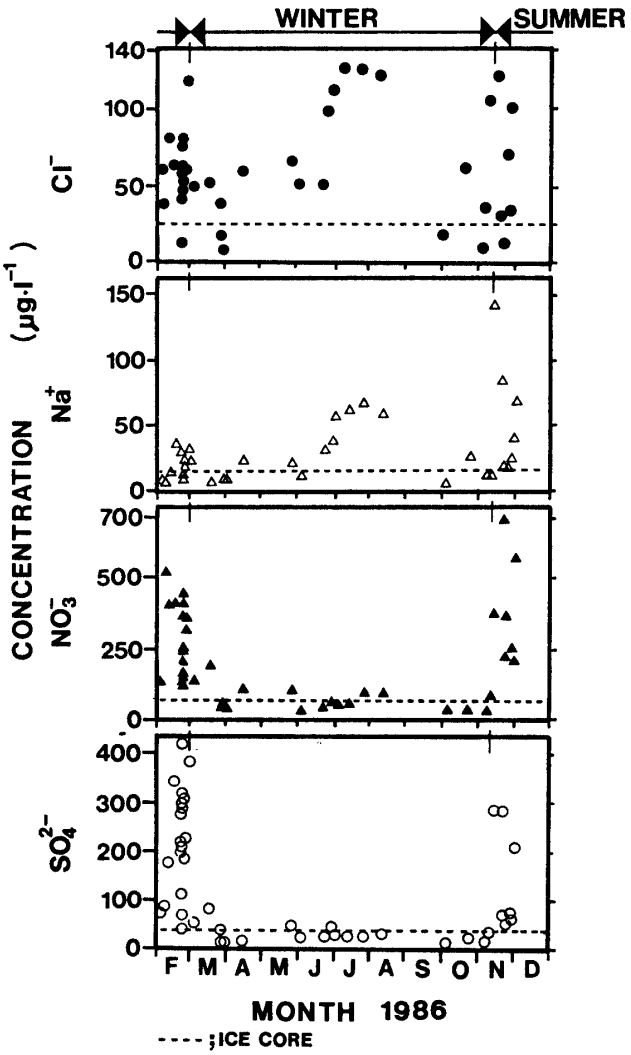

Fig. 1. Seasonal variations of concentrations ($\mu g \cdot l^{-1}$) of major constituents (OSADA et al., 1989). Dotted lines indicate mean concentration of major constituents in 700 m ice core collected at Mizuho Station (Y. FUJII et al., pers. commun.).

Table 1. Estimated mean concentrations of chemical constituents in snow drift and ice core ($\mu g \cdot l^{-1}$).

	Na^+	Cl^-	NO_3^-	SO_4^{2-}
Summer ($n=26$)	26	63	315	199
Winter ($n=18$)	24	63	67	29
Mean concentration in ice core (Y. FUJII *et al.*, pers. commun.)	15	39	56	51

drift" is defined as trapped snow in a small pit as described in detail in OSADA *et al.* (1989).

Since concentrations of NO_3^- and SO_4^{2-} in snow drift show a clear seasonal variation, one year is divided into two periods in the present paper; a period of high concentration (from November 15 to February 28: 106 days) which is called summer, and a period of low concentration (from March 1 to November 14: 259 days) which is called winter as shown in Fig. 1. Table 1 gives mean concentrations of Na^+, Cl^- NO_3^- and SO_4^{2-} in snow drift for each period, and the number of samples (n).

2.2. *Snow drift transport rate at Mizuho Station*

Table 2 shows the mean values of daily mean wind speed at 6.9 m above the snow surface and frequencies of drifting snow for each period, calculated from meteorological data over 4 years (TAKAHASHI *et al.*, 1983; NARITA *et al.*, 1985; YOSHIDA *et al.*, 1985; KIKUCHI *et al.*, 1986).

OHATA *et al.* (1982) pointed out that Mizuho Station has a strong concentration of surface wind direction, and the most frequent wind direction is east. Since this wind direction is about 30 degree counterclockwise from the fall line, snow drift transport rate (Q') in a unit time through the vertical plane of a unit width on the contour line is expressed by the following equation modified from KOBAYASHI (1978),

$$Q' = 10^{0.2U-0.12} \cos\theta \tag{1}$$

where θ is deviation angle of the prevailing wind from the fall line, U is wind speed 1 m above the snow surface, 0.2 and 0.12 are empirical values. θ is 30 degrees in the present

Table 2. Daily mean wind speed with drifting snow and frequencies of drifting snow for each period during recent 4 years.

Daily mean wind speed ($m \cdot s^{-1}$)	Frequencies of drifting snow (%)	
	Summer (106 days)	Winter (259 days)
≦ 5.9	0.5	0.2
6.0– 7.9	4.7	1.4
8.0– 9.9	17.7	10.6
10.0–11.9	21.7	24.7
12.0–13.9	9.7	26.4
14.0–15.9	3.6	17.0
16.0–17.9	0.3	6.7
18.0≦	0.3	2.0

case as mentioned above. Wind speed 1 m above the snow surface was estimated to be 84% of that 6.9 m above the snow surface according to TAKAHASHI (1985).

Snow drift transport rates are calculated from eq. (1) and the values from Table 2 for each period. Trasnport amounts by drifting snow for each period are 2.7×10^{9} kg·km^{-1}(1.6×10^{7} kg·km^{-1}·day^{-1}) in winter and 3.1×10^{8} kg·km^{-1} (3.0×10^{6} kg·km^{-1}·day^{-1}) in summer. The annual snow drift transport rate calculated from these values is about 3.0×10^{9} kg·km^{-1}·yr^{-1} which is the same order (from 1×10^{9} to 7×10^{9} kg·km^{-1}·yr^{-1}) reported from other stations in the katabatic wind region (LOEWE, 1970).

2.3. *Transport rates of chemical constituents by drifting snow*

Assuming that material concentration in snow drift at different heights above the snow surface is equal to that in snow drift collected just above the snow surface listed in Table 1, transport rates and amounts of chemical constituents for each period by drifting snow are calculated from mean concentrations in snow drift and snow drift transport rates for each period, as shown in Table 3. This table also gives annual transports of chemical constituents by drifting snow calculated from these values for each period.

Daily transport rates of Na^+ and Cl^- in winter are about 3 times as large as their transport rates in summer, whereas those of NO_3^- and SO_4^{2-} in winter are two thirds of these in summer. On the other hand, the snow drift transport rate in summer is 19% of the snow drift transport rate in winter. In other words, both amounts of Na^+ and Cl^- transport in winter occupy about 90% of the annual amounts, whereas those of NO_3^- and SO_4^{2-} in winter occupy about 60% of the annual amounts. Residual amounts of Na^+ and Cl^- (10%) and those of NO_3^- and SO_4^{2-} (40%) are transported in summer.

Differences in seasonal variation of transport among these chemical constituents is related to their origin and the atmospheric concentration. It is known that Na^+ and Cl^- in snow drift derive from sea-salt aerosol, whereas NO_3^- and SO_4^{2-} in snow

Table 3. Daily (10^2 g·km^{-1}·day^{-1}), annual and total (10^2 kg·km^{-1}·yr^{-1}) transport rates of chemical constituents by drifting snow and ice flow and proportions for each transport rates to total transport rates (%).

	Na^+	Cl^-	NO_3^-	SO_4^{2-}
	Daily (10^2 g·km^{-1}·day^{-1})			
Summer (106 days)	0.9 [0.1]	1.9 [0.2]	9.4 [1.0]	5.7 [0.6]
Winter (259 days)	2.3 [0.6]	6.6 [1.7]	6.9 [1.8]	3.1 [0.8]
	Drifting snow			
Annual (A1)	0.7	1.9	2.8	1.4
	Ice flow			
Annual (A2)	4.4	11	16	15
Total (A1+A2) (10^2 kg·km^{-1}·yr^{-1})	5.1	12.9	18.8	16.4
	Proportions for A1 and A2 to total (%)			
Drifting snow	14	15	15	9
Ice flow	86	85	85	91

[x]; transport amounts (10^2 kg·km^{-1}) of chemical constituents by drifting snow during each period.

drift are gas derived constituents (DELMAS *et al.*, 1982b; OSADA *et al.*, 1989). In both snow drift at Mizuho Station and aerosol at Georg Von Neumayer Station (70°S, 8°W), seasonal variations of concentrations of Na^+ and Cl^- (sea-salt) show maxima in winter and early summer, whereas those of NO_3^- and SO_4^{2-} (gas derived constituents) show maxima in summer (OSADA *et al.*, 1989; WAGENBACH *et al.*, 1988). Therefore, it is considered that differences in daily transport rates in the two seasons between sea-salt and gas derived constituents result from differences in seasonal variations in their concentrations in snow drift; nevertheless, the daily snow drift transport in winter is about 5 times that in summer.

3. Transport Rates of Chemical Constituents by Ice Flow

3.1. Chemical composition in ice core at Mizuho Station

Concentrations of Na^+, Cl^-, NO_3^- and SO_4^{2-} in the 700 m ice core collected at Mizuho Station in 1984 (Y. FUJII *et al.*, pers. commun.) are summarized in Table 1. These values are average values from 200 m to 700 m in depth. In the following section, transport rates of chemical constituents by ice flow are estimated, assuming that these values are equivalent to the average values between surface and bed rock.

3.2. Transport rates of mass and chemical constituents by ice flow

The transport rate (M) of mass by ice flow in a unit time through a vertical plane of unit width perpendicular to the flow direction is approximated by a rectangular box, assuming a uniform flow velocity between surface and bed rock. If the n-parameter of the flow law is 3, M is 80% of the amount calculated by using flow velocity at the surface; however, this parameter is expected to be more than 3. Therefore, it seems reasonable to assume that M can be expressed by a rectangular box.

From this approximation, M is expressed by the following simple equation;

$$M = V_s H W \bar{\rho} \tag{2}$$

where V_s is flow velocity at the surface, H is ice thickness, W is a unit width perpendicular to the flow direction and $\bar{\rho}$ is mean density of the entire thickness of ice. V_s at Mizuho Station is 16 $m \cdot yr^{-1}$ according to NISHIO *et al.* (1985). H is 2000 m at Mizuho Station (NISHIO *et al.*, 1986). $\bar{\rho}$ is 900 $kg \cdot m^{-3}$ for the entire depth. By introducing these values into eq. (2), M is calculated to be 2.9×10^{10} $kg \cdot km^{-1} \cdot yr^{-1}$ which is about 10 times mass transport by drifting snow. Table 3 shows the transport rates of chemical constituents by ice flow estimated from M and the mean concentration in ice.

4. Discussion

4.1. Differences in concentration between ice core and snow drift

As shown in Fig. 1 and Table 1, concentrations of chemical constituents in the ice core are about the same as those of snow drift in winter, but concentrations of NO_3^- and SO_4^{2-} in ice core differ from those of snow drift in summer.

Ice samples collected at Mizuho Station can be considered to have flowed from the upper region of Shirase Glacier. If concentrations of chemical constituents in

snow drift do not vary so much with altitude between 2000 m and 3000 m in Mizuho Plateau, concentrations of chemical constituents in the ice core are expected to be the same as concentrations in snow drift collected at Mizuho Station.

Therefore, differences in concentrations of chemical constituents between ice core and snow drift occur because deposition of snow drift in summer does not always form at altitudes from 2000 m to 3000 m, which is situated in the katabatic wind region. Indeed, deposition of snow drift is not always formed every month at Mizuho Station as indicated by snow stake measurements (FUJII and OHATA, 1982). Such a result suggests that interpretation of deposited flux of chemical constituents in snow and ice strata must be done carefully, because deposited amounts of chemical constituents in annual snow layers depend on snow accumulation season.

4.2. Comparison of transport rates of chemical constituents by drifting snow and ice flow

In previous sections, snow and ice mass transport rates by drifting snow and ice flow were estimated. The results in Table 3 indicate that transport rates of Na^+, Cl^-, NO_3^- and SO_4^{2-} by ice flow are 6, 6, 6 and 11 times those by drifting snow.

Table 3 also gives total transport rates of chemical constituents by drifting snow and ice flow, and ratios of transport rates of chemical constituents by drifting snow and ice flow to total transport rates. Transport rates of chemical constituents by drifting snow comprise 9% to 15% of total transport rates.

4.3. Annual transport of sulfate by drifting snow across the 2000 m contour

DALRYMPLE (1966) classified climatic regions over the Antarctic ice sheet. He found that the Cold Katabatic zone is widely distributed along the 2000 m contour. Everywhere in the Cold Katabatic zone, katabatic wind may drive drifting snow, and then chemical substances together with snow drift may be transported by katabatic wind from the middle part of the ice sheet to the coastal region through the year.

Since transport through the Antarctic atmosphere has been estimated for sulfate (DELMAS, 1982), transport of sulfate by drifting snow toward the coastal region below 2000 m is compared with his result. The area above 2000 m is about 7.5×10^6 km^2 according to the map of LEVANON (1982). The distance 9.7×10^3 km is the circumference of a circle which has the same area. Assuming that the sulfate transport (1.4×10^2 kg·km^{-1}·yr^{-1}) by drifting snow at Mizuho Station applies everywhere along the circumference of such a circle, transport of sulfate by drifting snow is calculated to be 1.4×10^6 kg·yr^{-1}.

On the other hand, DELMAS (1982) estimated that sulfate transport through a rectangular box ($3700\times3700\times5$ km: total area 14×10^6 km^2) is 1.5×10^9 kg·yr^{-1}. Transport of sulfate (1.4×10^6 kg·yr^{-1}) by drifting snow toward the coastal region below 2000 m is three orders smaller than that through the whole Antarctic atmosphere.

4.4. Possible errors in the present estimation in material concentration in snow drift and ice core

In Section 2.3, concentrations of chemical constituents in snow drift at different

heights above the snow surface were supposed to be the same as those in snow drift collected just above the snow surface. In some cases, concentrations of chemical constituents in snow drift increase with height above the snow surface. However, transports of chemical constituents by drifting snow should be slightly larger than those estimated above, because snow drift density is highest just above the snow surface.

On the other hand, estimated mean concentrations of chemical constituents in ice from surface to bed rock are uncertain, because concentrations of chemical constituents through much of the ice thickness are unknown. However, at Byrd Station, which has some similarity such as ice thickness, mean concentrations of chemical constituents in a 2000 m ice core were at most 1.5 times those in the upper 1000 m ice core (PALAIS and LEGRAND, 1985). From this example, mean concentrations of chemical constituents through the whole ice sheet at Mizuho Station are expected to be at most 1.5 times the value estimated in the present paper.

Accordingly, it is considered that the comparison of orders of these transport processes in the present paper is valid, because both transport rates increase in similar sense and order.

5. Concluding Remarks

The present study shows the important role of drifting snow in transport of chemical constituents across an altitude contour line in the katabatic wind region. It is necessary to pursue further studies on vertical profiles of concentrations of chemical constituents in snow drift, deposited snow and atmosphere in katabatic wind and other climatic regions to evaluate the material cycle over the present Antarctic ice sheet. These studies will contribute to interpretations of the past material cycle over the Antarctic ice sheet.

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